Femtoscopy of the system shape fluctuations in heavy ion collisions

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Abstract. Dipole, triangular, and higher harmonic flow that have an origin in the initial density fluctuations has gained a lot of attention as they can provide additional important information about the dynamical properties (e.g. viscosity) of the system. The fluctuations in the initial geometry should be also reflected in the detail shape and velocity field of the system at freeze-out. In this talk I discuss the possibility to measure such fluctuations by means of identical and non-identical particle interferometry.

The initial spatial conditions in heavy ion collisions are not azimuthally symmetric. Due to particle rescatterings it leads to the anisotropic flow – anisotropies in particle momentum distributions – with elliptic flow being the well known example. Recently, a significant progress has been reached in understanding the role of the initial density fluctuations. In particular it was realized that such fluctuations lead to odd harmonic anisotropic flow, studying of which brings new insights into dynamics of the system evolution. Below, I briefly summarize recent developments. I apologize for not providing the full list of references – many of which can be found in other proceedings of this conference.

An importance of the initial state fluctuations for flow development has been noticed in [1], though the exact relation between fluctuation and the final event anisotropies were not clear. In [2] an observation was made that non-zero two-particle rapidity correlations (as observed in *pp* collisions) in conjunction with radial flow (accepted part of the system evolution in *AA* collisions) lead to a narrow in azimuth and long ranged in rapidity correlations. Such correlations were observed experimentally and called *ridge*. This mechanism (non-zero "primordial" rapidity correlations + radial flow $\Rightarrow$ ridge) have been exploited later in several other models that try to address in more detail a (more subtle) question of the origin of the "primordial" rapidity correlations. Although the appearance of the ridge and anisotropic flow fluctuations look as totally unrelated phenomena, they appeared to be different views on the same thing – reaction of the system to the fluctuation in the initial density. In [3] it was shown explicitly that the fluctuations in the initial density distribution that extends over large rapidity range lead to the ridge structure in two particle correlations. It was also noticed that after subtraction of the expected contribution from elliptic flow, two-bump structure appears on the away-side. Further studies [4] with a single "hot spot" embedded into otherwise

smooth background appeared quite revealing. Contrary to an expectation [2] that such a hot spot moved out by the radial flow would create a "bump" in azimuthal distribution it appeared that that the hot spot actually "blocks" the development of the radial flow and leads to a "dip" in particle distribution at the corresponding azimuth, accompanied by side-splashes from both sides. Remarkably, in terms of the correlation function the "bump" and the "dip" leads to the same structure - the ridge, as both means *positive* correlations. At the same time, the exact shape of the correlation function (e.g. the strength of the third harmonic, which is important below) is different.

It was noticed in [5, 6] that the fluctuating initial conditions generate anisotropic flow of different harmonics. That followed by understanding [7, 8, 9] that the perturbations due to each of the hot spots can be treated independently, which allows to reformulate the problem from a different perspective – decompose the initial density into multipoles and study the system responce to each of the multipoles - the approach widely discussed at this conference as flow (dipole, triangular, quadrangular, etc.) fluctuations. One can envision such an approach as rotating each of the event to a given harmonic symmetry plane, such that at the end one could have a smooth initial conditions but with a shape corresponding to a given harmonic. The question addressed in this talk is if with the help of femtoscopy (identical and non-identical two-particle correlations) one can directly observe such triangular etc. shapes of the system. In this study I follow an approach of the first papers where the azimuthally sensitive femtoscopic analyses have been proposed [10, 11], and blast wave and AMPT models calculations.

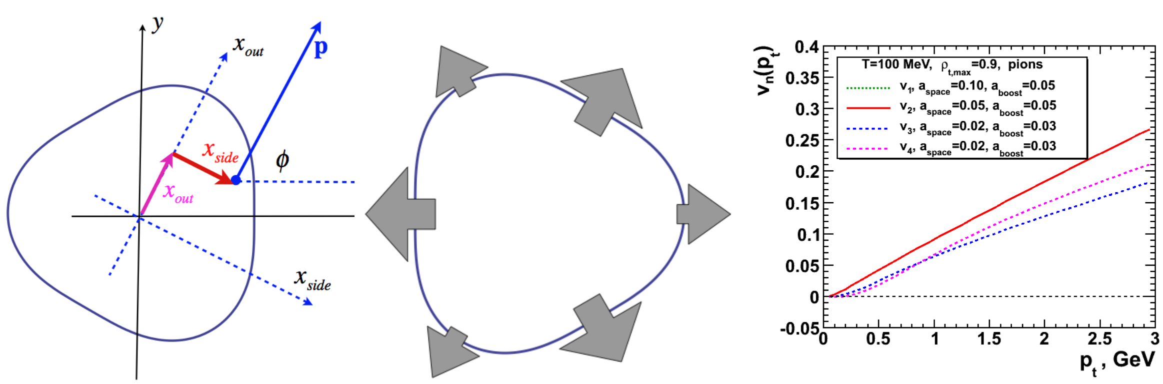

Figure 1. Left: side-out coordinates. Middle: illustration of predominant expansion along shorter directions. $v_n(pt)$ for typical values of parameters used in this work.

Intensity interferometry (identical particle femtoscopy), measures particle space-time distribution at freeze-out. Due to the probe on-mass constraint, the full space-time information can not be obtained, and one can access only the distribution in $(\mathbf{r} - \mathbf{V}t)$, where $\mathbf{r}$ is the particle position at time t (after freeze-out), and $\mathbf{V}$ is the particle velocity. For a Gaussian source, the correlation function appears to be a Gaussian

$$C(\mathbf{q}, \mathbf{P}) \propto 1 + \exp \sum_{i,j} R_{ij}^2 q_i q_j, \tag{1}$$

where $\mathbf{q} = \mathbf{p}_1 - \mathbf{p}_2$ is the pair relative momentum, $\mathbf{P} = (\mathbf{p}_1 + \mathbf{p}_2)/2 \approx \mathbf{p}_i$ is the

particle average momentum, and $R_{ij}^2 = \langle (r_i - V_i t)(r_j - V_j t) \rangle$ are the HBT radii. The deviation from a Gaussian form can be studied by evaluating the higher moments of the distribution (for the effect of non-Gaussiness on HBT radii, see [12]). Detailes of femtoscopic analyses can be found in a review [13].

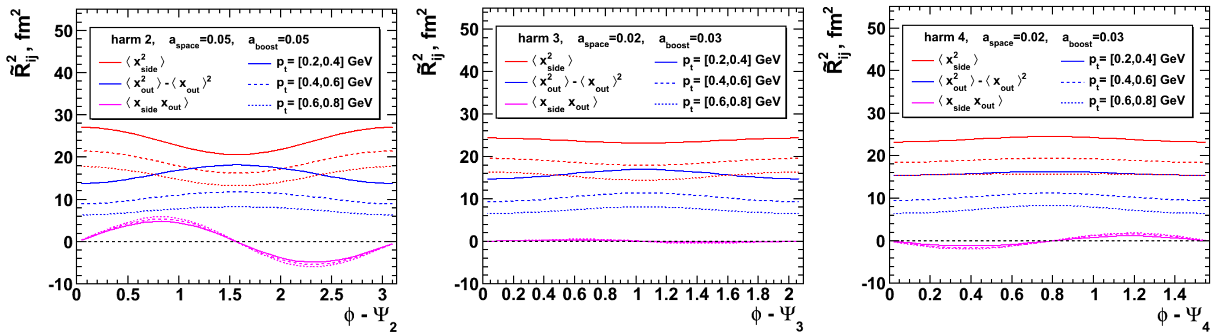

Figure 2. Blast wave model: HBT radii azimuthal dependence relative to the corresponding symmetry planes for harmonics 2, 3, and 4.

We use a standard side-out-long system [13] (see figure 1) and concentrate on azimuthal dependence of the side, out, and side-out radii. For a *stationary* (not expanding) source the radii azimuthal dependence can be expressed as

$$R_{side}^2 = \langle x_{side}^2 \rangle = \langle x^2 \rangle \sin^2 \phi + \langle y^2 \rangle \cos^2 \phi - \langle xy \rangle \sin 2\phi, \tag{2}$$

which has only $n = 2$ harmonic. Higher harmonics azimuthal dependence appears only as deviation from the Gaussian, e.g. in $\langle x_{side}^6 \rangle$ and $\langle x_{side}^4 \rangle$ for triangular and quadrangular shapes respectively. The picture changes if one considers azimuthal variation in the expansion velocity. To study this effect we employ a blast wave model. We assume longitudinally boost invariant source and freeze-out at a constant temperature $T = 100$ MeV. Expansion velocity profile is parametrized in a form

$$\rho_t(r, \phi) = \rho_{t,max} \frac{r}{r_{max}(\phi)} [1 + a_{boost} \cos(n\phi)], \tag{3}$$

$$r_{max} = R[1 + a_{space} \cos(n\phi)], \tag{4}$$

with direction of the collective velocity being perpendicular to the line $\propto [1 + a_{space} \cos(n\phi)]$ going through the emission point. The parameter $\rho_{t,max} = 0.9$ which corresponds to an average expansion velocity $\langle v_r \rangle \approx 0.7$ and $\langle p_t \rangle_\pi = 0.40$ GeV. a_{space} and a_{boost} parameters define the spatial eccentricity at freeze-out and modulation in the expansion velocity. For the first we assume that the system spatial eccentricity is reduced about two times during the system evolution, which leads to $a_{space} \sim 0.05$; a_{boost} can be estimated from $v_n(p_t)$ dependence and is taken to be in the range 0.03-0.07. The azimuthal dependence of the obtained HBT radii, see figure 2, indicates that the higher harmonics shape effects become clearly visible (and measurable). Note the difference in the amplitudes of $R_{side-out}$ terms. The radii modulation strongly depends on the parameters of the model, and the correspondng measurements will be very important in evaluating the velocity profiles at freeze-out and testing models.

The AMPT model [14] has been extensively used in studying the effect of the initial state fluctuations. We use this model to study Au+Au collisions at $\sqrt{s_{\rm NN}}$=200 GeV. Figure 3 shows the HBT radii variation as function of the azimuth relative to a given harmonic *event plane* which includes the effects of finite reaction plane resolution. Once again, the radii dependence on the azimuth is clearly seen. A detailed investigation of the side-out relative phases, dependece on the particle transverse momentum, etc. requires additional investigations.

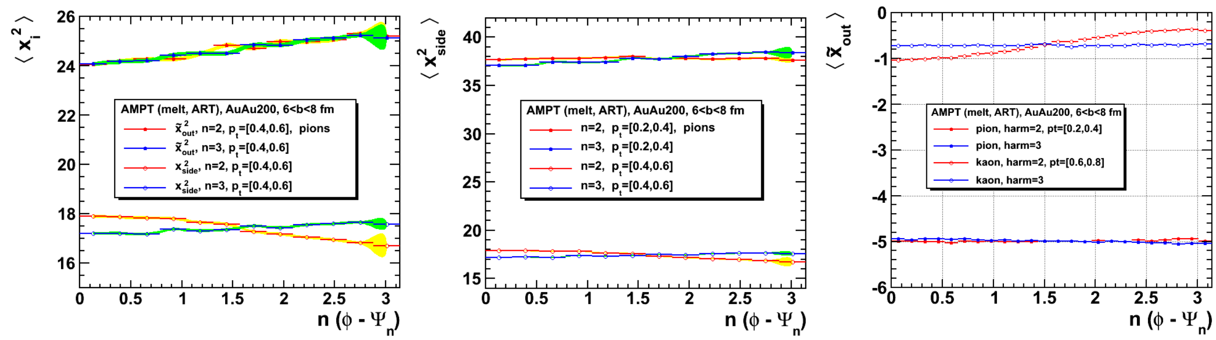

Figure 3. AMPT model: the azimuthal dependence of the HBT radii (left and middle), and radial shift in the production points of kaons and pions, $\tilde{x}_{out} = x_{out} - V_t t$, at $p_t \sim 1.5\,m$.

<u>*Summary.*</u> Using the blast wave and AMPT models we have demostrated the possibility of femtoscopic higher harmonics system shape analysis that promices new insights into the physics of heavy ion collisions.

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